

Analysis of global climate model experiments to elucidate past and future changes in surface insolation and warming in China

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[1] Trends in climate variables and their interrelationships over China are examined using a combination of observations and global climate model simulations to elucidate the mechanism for producing an observed 1°C increase in surface temperature despite a significant decrease in surface insolation from 1950 to 2000. For the 21st century, the model simulations suggest that the downward trend in insolation is expected to continue until 2050, primarily forced by the prescribed atmospheric sulfate burden (IPCC SRES A1B). A continuous increase in surface temperature (3°C) and vapor pressure (1mb) is simulated during the 21st century. Our analysis suggests that both the past and the future warming are primarily caused by an increase in downward longwave radiation. This occurs, in part, as a result of both the lower and upper atmospheric water vapor feedbacks, triggered by the increase in anthropogenic greenhouse gases. **Citation:** Rangwala, I., J. Miller, G. L. Russell, and M. Xu (2006), Analysis of global climate model experiments to elucidate past and future changes in surface insolation and warming in China, *Geophys. Res. Lett.*, 33, L20709, doi:10.1029/2006GL027778.

1. Introduction

[2] There have been several recent papers reporting significant changes in climate variables over China during the latter half of the 20th century [Kaiser, 2000; Thomas, 2000; Kaiser and Qian, 2002; Liu et al., 2004a; Liu et al., 2004b; Liu et al., 2005; Qian et al., 2006]. These variables include surface insolation, surface air temperature, cloud cover, surface vapor and air pressure, precipitation and evaporation. The changes have both spatial and temporal variability. The observations suggest (a) an increase in surface air temperature [Liu et al., 2004b], (b) reductions in daily temperature range [Liu et al., 2004b], insolation [Liu et al., 2004a; Kaiser and Qian, 2002; Qian et al., 2006] and estimated potential evapotranspiration [Thomas, 2000] for most geographical regions, (c) a decrease in cloud amount [Kaiser, 2000; Qian et al., 2006], (d) an increase in surface air pressure [Kaiser, 2000], and (e) an increase in the intensity and reduction in the frequency of precipitation, except in northwest China [Liu et al., 2005].

[3] The causes for these changes are not yet clearly understood. It is possible that some combination of both global- and regional-scale forcings has led to the observed behavior of the climate variables. On the global scale, the increase in radiative forcing due to increasing greenhouse gases and the associated changes in atmospheric circulation are likely to have caused a portion of the observed changes. At the regional scale, the climate variables could be influenced by the increase in atmospheric aerosols caused by the rapid rate of development in China over the last 5 decades of the 20th century [e.g. Giorgi et al., 2003; Qian et al., 2003]. Large-scale land-use changes may also be a factor [Fu, 2003]. An equilibrium modeling study by Menon et al. [2002], using the GISS SI2000 12-layer model, reported that the alteration in the regional atmospheric circulation caused by the direct radiative effects of black carbon aerosols over China, produced the observed temperature and precipitation trends over China. These regional trends primarily include increase in summer floods in south China and drought in north China, and moderate cooling in southeast China.

[4] Our study analyzes simulations from the global coupled atmosphere-ocean model based on Russell et al. [1995] to elucidate the underlying mechanisms that are likely to have caused the observed warming over China from 1950–2000 despite significant decreases in surface insolation over most of the region. Both the global- and regional-scale forcings are likely to persist, even intensify, in the first half of the 21st century. It is, therefore, crucial to understand the trends in climate variables that might emerge as a result of expected changes in the global and regional forcings during the 21st century. This study will examine potential changes in the climate variables for the 21st century over China. The observations and the model are described in the next section. Section 3 describes the observed and modeled changes for the last half of the 20th century and section 4 describes the projected changes in the 21st century. A discussion is found in section 5.

2. Description of Observations and Model

[5] The observed variables in this study include annual mean measurements of surface air temperature, surface insolation, cloud cover, and surface vapor pressure. The observations for surface insolation (85 stations) and vapor pressure (305 stations) from 1954 to 2000 are obtained from Liu et al. [2004a], and their trends are consistent with sunshine duration and vapor pressure trends reported in Kaiser and Qian [2002] and Kaiser [2000], respectively. The annual mean surface temperature observations from 1955 to 2000, from 305 stations, are obtained from Liu et al. [2004b]. The observations for cloud cover from 1954–

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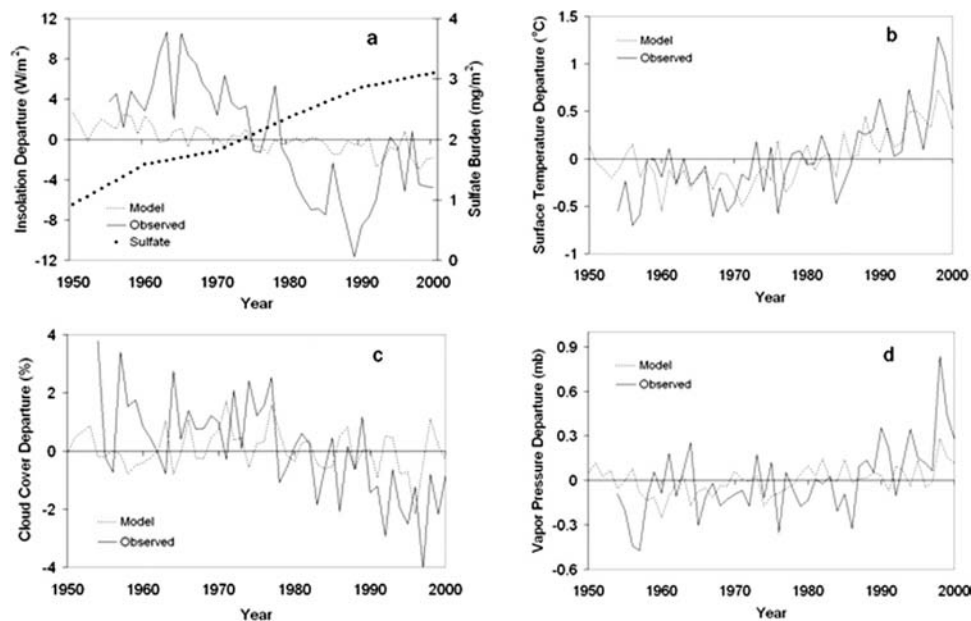


Figure 1. Departures from the 1950 to 2000 mean for observations and model for (a) insolation, W/m^2 [Liu et al., 2004a] and atmospheric sulfate burden, mg/m^2 [Boucher and Pham, 2002] (b) surface temperature, $^{\circ}\text{C}$ [Liu et al., 2004b], (c) cloud cover, % [Qian et al., 2006], and (d) surface vapor pressure, mb [Liu et al., 2004b].

2000, from 537 stations, are obtained from Qian et al. [2006] which closely correlate with the cloud cover data from 1954–1996 in Kaiser [2000] from 196 stations. Information on the quality of data and the methodology used for averaging, wherever applicable, is discussed in the supplementary materials.¹

[6] The 4×3 degree grid global coupled atmosphere-ocean model, GISS-AOM (Goddard Institute of Space Studies – Atmosphere Ocean Model, NASA), based on Russell et al. [1995; <http://aom.giss.nasa.gov>] is used to simulate trends in the selected climate variables over China. Most of the model results presented here are based on outputs from a single model experiment (GHG + Sulfate). The initial state of this simulation was based on a 200 year spin-up run of initial ocean conditions [Levitus et al., 1994]. From 1850 to 2000, this simulation uses observed greenhouse gases and estimated spatial distributions of atmospheric sulfate burden from Boucher and Pham [2002] (Figure 1a). For the 21st century, greenhouse gases are observed up to year 2003 followed by SRES A1B; the sulfate burden is from SRES A1B [Pham et al., 2005]. Two additional model experiments whose results are presented here are (a) the control experiment, which keeps the atmospheric composition fixed at 1850 values, and (b) the GHG experiment, which keeps sulfate aerosols fixed at 1850 values.

3. Observed and Modeled Climate Change From 1950–2000

[7] Figure 1 shows that there is a decreasing trend in surface insolation and cloud cover and an increasing trend in surface temperature and water vapor pressure in both

model and observations (see also Table 1). Between 1950 and 1975, there is no appreciable trend in cloud cover, temperature and surface vapor pressure in the observations or model simulation. For the same period, both model and observations show a decrease in insolation. Modeled and observed trends presented hereafter are from 1950–2000. The observed reduction in insolation is 3.27 W/m^2 per decade which is significantly greater than the model reduction of 0.68 W/m^2 per decade (Figure 1a). The observed increase in surface temperature in China is 0.19°C per decade [Liu et al., 2004b], compared to 0.12°C per decade for the model (Figure 1b).

[8] Most of the simulated increase in surface vapor pressure occurs after 1975, which is similar to the modeled trends in temperature (Figure 1d). The simulated increase in vapor pressure in the upper (200 mb) and middle troposphere (500 mb) is 9% and 4%, respectively; it is 2% at the surface. The sudden decrease in observed cloud cover, -0.73% per decade, starting around 1975 (Figure 1c) is correlated with the rise in temperature ($r = -0.52$). The model, however, shows a much smaller decrease in cloud cover although the correlation of the latter with temperature ($r = -0.47$) is similar.

[9] The reduction in surface insolation over China appears to be primarily forced by the atmospheric aerosol loading (Figure 1a). This is further supported by noting that there is a decreasing trend (modeled and observed) in cloud cover (Figure 1c). The partial correlation between the observed insolation and sulfate aerosol trends from 1955 to 2000 is -0.81 , and between the observed insolation and cloud cover is -0.45 . The spatial distribution of sulfate aerosols in the model is similar to the observed mean aerosol extinction coefficient (AEC) across China from 1984–1998 estimated by Kaiser and Qian [2002]. Sulfate aerosols in the model affect the radiation directly, but their indirect effects on clouds are not included in the model.

¹Auxiliary materials are available in the HTML. doi:10.1029/2006GL027778.

Table 1. Observed and modeled trends (per decade) in climate variables over China for three time periods: 1950–2000, 1950–1975 and 1975–2000

Climate Variables	1950–2000		1950–1975		1975–2000	
	Observed	Model	Observed	Model	Observed	Model
Sulfate Burden (mg/m^2)	+0.57	–	+0.59	–	+0.55	–
Insolation (W/m^2)	–3.27	–0.68	–3.85	–0.70	–2.69	–0.68
Temperature ($^{\circ}\text{C}$)	+0.19	+0.12	+0.01	–0.07	+0.38	+0.31
Cloud Cover (%)	–0.73	–0.08	–0.30	+0.08	–1.22	–0.24
Vapor pressure (mb)	+0.08	+0.03	–0.01	–0.02	+0.17	+0.07

For each climate variable, 51 annual values were least square fitted to a parabola. The trends are equal to ten times the slope of the parabola over the various time periods.

Furthermore, the model could capture only 21% of the observed reduction in surface insolation, which suggests that either black and organic carbon aerosols, and dust have a greater role to play in the observed solar dimming over China than sulfate aerosols alone [Chameides *et al.*, 1999; Qian *et al.*, 2003], or the model insolation has lower sensitivity to changes in sulfate aerosols.

[10] It is interesting to note that, in both model and observations, the surface temperature over China increases during the same period when surface insolation decreases with the contrast being much greater in the observations. The increase in surface temperature could be caused by an increase in downward longwave radiation (DLR) due to the increase in greenhouse gas forcing and the associated water vapor feedbacks, which overcompensates for the reduction in insolation. The partial correlation between the observed CO_2 and temperature trends from 1959–2000 is 0.70, and between the observed surface vapor pressure and temperature is 0.75. However, there is a weak correlation ($r = 0.34$) between the observed CO_2 and surface vapor pressure. Moreover, the partial correlation between the modeled DLR and CO_2 from 1950–2000 is 0.77, and between the modeled DLR and surface vapor pressure is 0.83.

[11] The model's DLR, which is affected by greenhouse gases and clouds, increases by $4.3 \text{ W}/\text{m}^2$ while the insolation decreases by $3.4 \text{ W}/\text{m}^2$ from 1950–2000. Assuming other variables are constant, the change in surface temperature associated with a change in DLR can be estimated using the relationship, $\Delta B/B = 4 \cdot \Delta T/T$, derived from the Stefan-Boltzmann law for black body radiation, where ΔB and ΔT are changes in DLR and temperature, respectively. This calculation yields $\Delta T = 1.03^{\circ}\text{C}$ when $\Delta B = 4.3 \text{ W}/\text{m}^2$. However, the model simulates a surface temperature increase of 0.61°C from 1950–2000. The discrepancy between the calculated and the modeled surface temperature increase is likely caused, in large part, by a $0.6 \text{ W}/\text{m}^2$ decrease in insolation absorbed by the surface between 1950 and 2000 (Figure 2c). Furthermore, the discrepancy between the observed and modeled rate of surface warming by a factor of 1.5, from 1950–2000, is likely caused by a 2.5 times higher rate of increase in the observed surface vapor pressure (Figure 1d; see also Table 1), which could amplify the DLR from the near surface atmosphere.

[12] Philipona *et al.* [2005] present a similar scenario for warming in Central Europe from 1995–2002. Their ground based radiation measurements show a decrease in annual average insolation of $1.1 \text{ W}/\text{m}^2$ and an increase in annual average DLR of $5.3 \text{ W}/\text{m}^2$. This leads to an increase of 0.8°C in annual average temperature. They separate different forcings contributing to the increase in DLR from

increases in (a) clouds ($1.4 \text{ W}/\text{m}^2$), (b) greenhouse gases except water vapor ($0.35 \text{ W}/\text{m}^2$), (c) water vapor ($0.79 \text{ W}/\text{m}^2$) and (d) temperature ($2.72 \text{ W}/\text{m}^2$) to suggest that the water vapor forcing in the lower atmosphere is about 2.3 times the anthropogenic greenhouse gas forcing in the regions where sufficient water is available for evapotranspiration.

[13] An additional mechanism that could produce surface warming in spite of a significant decrease in surface insolation over China during the latter half of the 20th century,

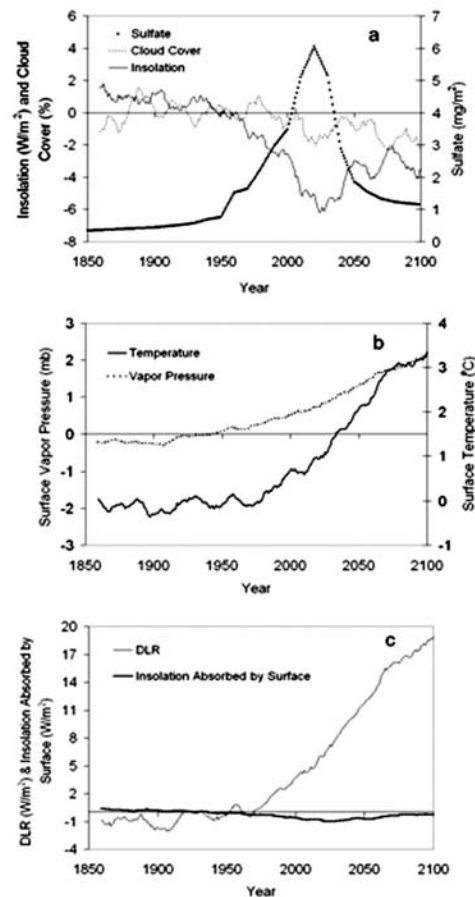


Figure 2. Departures in (a) insolation (W/m^2) and cloud cover (%), (b) surface temperature ($^{\circ}\text{C}$) and vapor pressure (mb), and (c) DLR (W/m^2) and insolation absorbed by the surface (W/m^2) simulated over China from 1850 to 2100. Simulations are 10 year running mean of annual departures from the 1850–1999 mean. Annual mean values of the atmospheric sulfate burden (mg/m^2) shown are based on Pham *et al.* [2005].

particularly from 1970 to 1995, is a relatively greater reduction in latent heat fluxes to compensate for the decrease in surface insolation. *Liepert et al.* [2004] performed equilibrium climate simulations to elucidate the changes in the global terrestrial surface energy budgets between the pre-industrial (1880s) and the present day (1980s) situations produced by the difference in the atmospheric loading of greenhouse gases and aerosols. Their model, which included parameterizations for both direct and indirect aerosol effects, showed a relatively greater reduction in the strength of latent heat fluxes in the present day scenario, to compensate for the reduction in surface insolation. Their model also produced a 0.6°C warming in the present day condition despite a 0.52 W/m^2 decrease in the net surface insolation.

[14] The direct observation of evaporation across China is unavailable. However, measurements of potential evapotranspiration from observed meteorological data over China from 1951–1993 show a significant decreasing trend (*Thomas*, 2000). Decreases in potential evapotranspiration south of 35°N are most strongly associated with sunshine duration. Our model suggests a small decrease in evaporation (-1.3 mm/decade) from 1950 to 2000. The simulated decrease in evaporation would be greater if black and organic carbon aerosols and aerosol indirect effects are included in the model [*Ramanathan et al.*, 2001; *Roderick and Farquhar*, 2002].

[15] Overall, the modeled trends in the climate variables discussed above have the same sign as the observed, although the modeled changes in surface insolation, temperature and vapor pressure are smaller than the observed changes. The sharp increase in temperature during the latter half of the 20th century despite “solar dimming” appears to occur, in part, because of the simultaneously increasing greenhouse gas forcing and associated water vapor feedbacks. Overall, the model appears to offer a conservative estimate of the change in the climate variables discussed here. In the next section, we examine the trends and interrelationships among these variables for China during the 21st century under the prescribed forcings of greenhouse gases and atmospheric sulfate burden.

4. Modeled Climate Change From 1850–2100

[16] The modeled surface insolation shows a small declining trend between 1850 and 1950, following which there is a sharp and continuous decline in insolation by 6 W/m^2 by the year 2020 (Figure 2a). This appears to be caused by the increase in atmospheric sulfate burden. In fact, a gradual reduction in annual cloud cover is predicted by the model for the 21st century (Figure 2a), which will enhance the insolation during that period. Insolation increases in the latter half of the 21st century; however, it does not reach the pre-1950 values even under the decreasing cloud cover trend during the 21st century. This is because the atmospheric sulfate burden is still above pre-1950 values.

[17] In spite of a decrease in surface insolation of 6 W/m^2 (from the 1850–1999 mean) in the first half of the 21st century, followed by a recovery of 2 W/m^2 in the latter half, a continuous increase in surface temperature is simulated for the entire 21st century over China. The 3°C temperature increase from 1975–2100 (Figure 2b) appears to be related to an increase in the DLR of 19 W/m^2 over China for the

same time period ($r = 0.98$; Figure 2c), which is significantly greater than the increases in sensible heat (0.6 W/m^2) and latent heat (3.5 W/m^2) fluxes. Our calculation suggests that for a DLR increase of 19 W/m^2 the temperature increases by about 3.8°C , which is slightly higher than the simulated increase in surface temperature (3°C). This difference could be partly due to a concomitant decrease in insolation absorbed by the surface during the 21st century (Figure 2c). The partial correlation of the modeled DLR during the 21st century, with atmospheric CO_2 concentration and surface vapor pressure is 0.79 and 0.80.

[18] Modeling experiments [*Hall and Manabe*, 1999] as well as the analysis of observed climate variables [*Rakoczi and Ivanyi*, 1999–2000] have shown that the water vapor feedback induced by atmospheric warming, which is triggered by an increase in anthropogenic greenhouse gases, is a much more important mechanism in amplifying DLR than the anthropogenic greenhouse gases. Moreover, the water vapor feedback is a combination of both the lower and the upper tropospheric water vapor feedback. The midlatitude atmospheric boundary layer over China may not be optically saturated to the longwave radiation from the surface. Therefore, an increase in the lower atmospheric water vapor content can directly increase the infrared heating of the surface. The modeled increase in surface vapor pressure at the end of the 21st century is 15% higher than the 1850–1950 mean, a period during which there is little change in surface vapor pressure (Figure 2b).

[19] Moreover, the modeled increase in vapor pressure during the 21st century is 25% at 500 mb and 80% at 200 mb, which is similar to the results from another GCM simulation performed by *Soden et al.* [2005]. They analyzed satellite measurements of clear-sky radiances, which are sensitive to water vapor concentration in the upper troposphere, to demonstrate moistening of the upper troposphere from 1982–2000. This observed moistening is also in accord with the increase in moistening of the upper troposphere simulated with satellite-observed sea surface temperatures. The outgoing longwave radiation is suggested to be very sensitive to the changes in the upper tropospheric humidity [*Held and Soden*, 2000]. Therefore, the moistening of the mid and upper troposphere can make the troposphere substantially more opaque to outgoing longwave radiation, thereby warming the troposphere as a whole and contributing to warming the surface and the lower troposphere in the 21st century. However, the relative importance of the lower and upper level water vapor feedbacks in increasing the DLR over China could not be quantified from our modeling experiments.

[20] Cloud cover, which can also significantly affect DLR, is decreasing during the 21st century (Figure 2a), and is, therefore, not expected to cause the simulated increase in DLR (Figure 2c). Comparison of trends in climate variables between the GHG + Sulfate and GHG experiments shows that atmospheric sulfate will tend to suppress the warming until the middle of the 21st century (Figure 3a). A smaller increase in surface temperature between 1960 and 2060 in the GHG + Sulfate experiment is accompanied by a smaller increase in surface vapor pressure (Figure 3c), and consequently a smaller increase in DLR (Figure 3b), in comparison to the GHG experiment. As the difference in surface insolation between the two

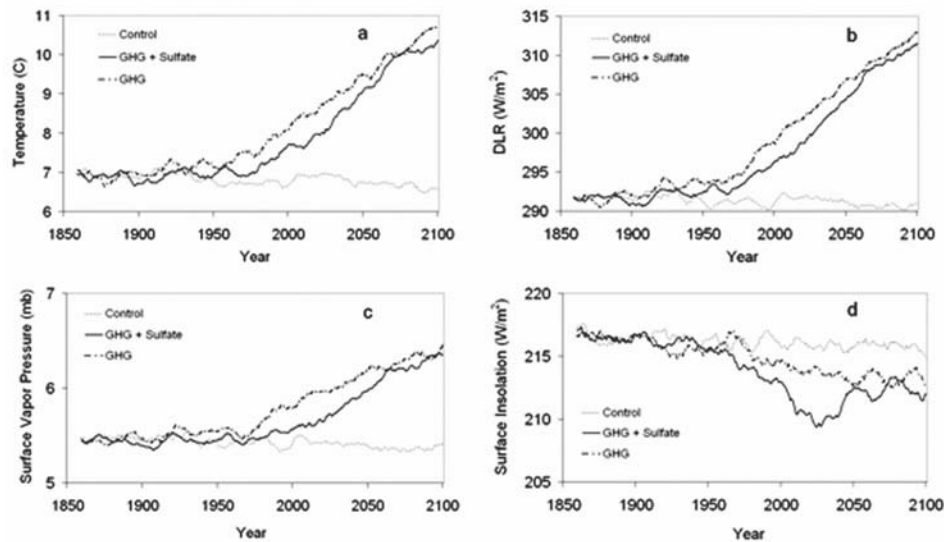


Figure 3. Trends in (a) temperature ($^{\circ}\text{C}$), (b) DLR (W/m^2), (c) surface vapor pressure (mb) and (d) surface insolation (W/m^2) over China from three different model experiments having (1) no greenhouse and sulfate aerosol forcings (Control), (2) greenhouse forcing only (GHG) and (3) both greenhouse and sulfate aerosol forcings (GHG + Sulfate). Line plots are 10 year running mean. Outputs from the GHG experiment were corrected for the offset over the whole period.

experiments becomes smaller after 2060, there are smaller differences between the two experiments for temperature, vapor pressure and DLR.

5. Discussion

[21] The simulation of climate variables for China from 1950 to 2000 by the GISS-AOM model produces similar trends as observed although the magnitude of the modeled changes is smaller. The observed warming of 1°C from 1950 to 2000 despite a $3.27 \text{ W}/\text{m}^2$ per decade decrease in surface insolation appears to be in large part the result of an increase in DLR, which is a consequence of an increase in anthropogenic greenhouse gases and the associated atmospheric water vapor feedbacks. The surface vapor pressure over China increases by 0.40 mb during that period. Philipona *et al.* [2005] suggest that an increase in DLR resulting from an increase in surface vapor pressure, triggered by an increase in anthropogenic greenhouse warming, caused the bulk of surface warming observed in Central Europe from 1995–2002 in spite of a decreasing trend in surface insolation.

[22] For the 21st century, the model predicts a downward trend in surface insolation until the middle of the 21st century forced by the atmospheric sulfate burden, after which it has an upward trend as the atmospheric sulfate burden decreases. The model also predicts a continuous rise in surface temperature and surface vapor pressure during the 21st century. These changes are much greater than for the period from 1850–2000.

[23] Surface warming in China during the 21st century despite the decreasing trend in surface insolation, is caused by a combination of changes in energy budgets near the surface and in the upper atmosphere. Near the surface, an increase in surface vapor pressure, triggered by an increase in anthropogenic greenhouse gases, lead to increased infrared heating of the surface. In the upper troposphere, a

decrease in the outgoing longwave radiation, due to an increase in greenhouse gases and the associated upper-troposphere water vapor feedback, would produce a general warming of the troposphere which will be transmitted to the surface. The outgoing longwave radiation at the top of the atmosphere is highly sensitive to changes in upper tropospheric humidity and the observations suggest that the latter has increased in the past two decades in accord with the predictions made by most GCMs [Soden *et al.*, 2005].

[24] Exclusion of the indirect aerosol effects as well as the direct radiative effects of black and organic carbon aerosols, and mineral dust in the model are likely to have caused the conservative prediction of the changes in climate variables from 1950–2000. Therefore, the large changes in annual mean insolation, temperature and vapor pressure at the surface predicted by the model for China in the 21st century, may also be conservative estimates.

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